SCOS97 3-D Commercial Aircraft Emissions Methodology

I. Introduction.

This document describes the ARB methodology for calculating three-dimensional, day-specific aircraft emissions. It is compared with the South Coast Air Quality Management District (SCAQMD) method.

II. The South Coast Air Quality Management District Method.

The SCAQMD used the standard method of defining annual takeoffs and landings, at airports in the domain (from the airports themselves or from Ref. 2), aircraft types from Ref. 2, engine types from Ref. 3, times in modes from Ref. 4, engine emissions factors from Ref. 4.

Their method only considers climbout to the top of the inversion layer, and descent within this layer. The nominal climbout time through the inversion layer (Ref. 4), was scaled by inversion layer thickness for each airport. Taxi/idle times for takeoff and landing were different for, and obtained from, each airport.

Hence, by the nature of this standard approach, it cannot give emissions information at altitude, or away from the airports. However, it is simple and direct, and does not require extensive code and computer resources.

III. The Air Resources Board Method.

The ARB method consists of three parts:

a) Pre-processing of FAA aircraft flight data files, and of US EPA Engine Emissions Data (70% of effort)

b) Development and use of the gridding code in FORTRAN, to calculate aircraft emissions in the SCOS97 domain (25% of effort)

c) Post-processing of gridding code results, to generate emissions summaries and graphical results (5% of effort).

This activity has used approximately 2 person years, from May 1999 to date.

IV. Pre-Processing of FAA Aircraft Flight Data Files and US EPA EDMS Engine Emissions Data.

Flight track data were obtained from a vendor who processes FAA (Federal Aviation Agency) radar transponder returns (Ref. 5). These files consist of flight plan, flight departure, flight track, and flight arrival files by day, in comma-delimited format, for several SCOS97 episode periods of interest:

1) 1-5 July 1997

2) 2-8 August 1997

3) 21-28 August 1997

4) 2-13 September 1997

5) 21 September – 5 October 1997

6) 29 October – 2 November 1997

There are approximately 360,000 flight tracks (i.e. about 6,000 per day in and out and over Southern California), of all types of aircraft, in these files. Approximately one third (2,000) of the daily tracks are commercial jets. The files contain approximately 3.7 million records, of which 90% are in the flight track files. The data for 8 August is incomplete, with only about ¼ of a day of data.

Files for each day, in comma delimited format, show aircraft type, flight plans, arrivals, departures and flight tracks of aircraft passing through Southern California air traffic control, which is approximately the southern third of the state.

These data were combined into complete flight tracks, and merged into a binary, direct access dataset, where a specific flight track could be accessed by FAA flight number, or by date and GMT (Greenwich Mean Time) for the first point in the flight track. GMT is the time base used in the FAA flight track datasets.

The FAA aircraft flight data files included landings files for each of the days of the SCOS97 episodes, with approximately 360,000 total entries (FAA flight number, message time, message date, FAA aircraft type, landing airport 4-character code). The entries were in almost random order of FAA flight number and message time and date. FAA flight numbers are not unique – they are cycled approximately every 3 months. Therefore, we generated unique flight numbers where the FAA flight numbers repeated. All of this was combined into a single landings dataset file. This file was sorted on the basis of FAA flight number, message time and message date.

The FAA aircraft flight data files similarly included takeoff files for each of the days of the SCOS97 episodes, also with approximately 360,000 total entries. Data were similar to the landings files, except that the airport code was for the takeoff airport. These files were processed in a manner similar to the landings files, into a single, sorted takeoffs dataset file.

The FAA aircraft flight data files included flight plan files for each of the days of the SCOS97 episodes, with approximately 360,000 total entries. The records were transcripts of hand-written or typed, submitted flight plans. As usual, the entries were in almost random order of FAA flight number and message time (being combinations of data from various FAA flight control centers). FAA flight numbers were not unique. Records were of variable length, containing FAA flight number, message time, message date, FAA aircraft type, airline variable length character string aircraft ID, takeoff and landing airports' 4-character codes. In addition, the record contained a variable length sequence of 4-character and 3-character codes specifying the aircraft navigation beacons over which the aircraft was to fly. There were errors in aircraft type, takeoff and landing, and aircraft navigation beacon character codes: All of these codes occasionally change, and personnel would use obsolete codes, or mistyped them.

The records in these files were assigned unique FAA flight numbers, and sorted by FAA flight number, message time and message date, resulting in the flight plans dataset file.

Finally, the FAA aircraft data files included flight track files for each of the days of the SCOS97 episodes, with approximately 3.7 million total entries. The records included FAA flight number, message time and date, aircraft position time and date, aircraft navigation beacon 3- or 4-character code (which defined position), FAA aircraft type 4-character code, airline aircraft ID (variable length character string), speed (knots), and altitude (feet/100) above mean sea level. Altitude was very noisy, with tens of thousands of 'dropouts' to zero altitude, or to a default 10,000 feet (depending upon radar transponder type and characteristics). Speed was also somewhat noisy. Data were particularly bad near the ends of the flight tracks, when altitude was low – presumably due to masking, scattering and multiple returns from terrain.

The flight track data files were sorted by FAA flight number, aircraft position time and date, and combined into the flight track dataset file.

At this point, the landings, takeoffs, flight plan and flight track data sets were checked for consistency: correspondence of FAA aircraft type, airline ID, correct spellings of takeoff airport, landing airport and navigation beacon codes. Mistakes occurred in approximately 0.5% of the data (1,800 flights). Special processing was required for flight numbers which were not in all of the files (approximately 1.5% or 5,400 flight numbers): missing data was estimated. Approximately 1/3rd of the flight tracks had 'blank' FAA aircraft types. These were subsequently accepted or rejected as commercial jets, on the basis of a mean aircraft speed along the flight track of 250 knots or greater. Approximately 1/3rd of the flight tracks were not commercial jets (most were general aviation), on the basis of the FAA aircraft types; these were not used in subsequent analysis.

From AOPA (Aircraft Owners and Pilots Association) manuals, an aircraft navigation beacon and airports dataset was constructed, defining beacon or airport 3- or 4-character ID codes, elevation above msl, longitude and decimal, latitude and decimal. This comprised approximately 650 airports and beacons in the Western U. S. This dataset was used to insert longitudes and latitudes at each landing and takeoff point, and at each flight track point. Aircraft engine operating mode was estimated for each flight track point, from aircraft position, speed, altitude, and proximity to an airport. Time points were inserted into the trajectories, to transition from auxiliary power unit (APU) only to taxi/idle + APU, taxi/idle to takeoff, takeoff to climbout, climbout to cruise, cruise to descent, descent to taxi/idle + APU, taxi/idle to APU only, APU shutdown. This was based upon US EPA guidelines for operating mode times, and upon SCAQMD inversion layer thicknesses at the various airports in the SCOS97 domain, i.e., the developed dataset is airport-specific.

All of the above data were put into a combined flight track dataset, sorted by flight track start time and date, for the approximately 360,000 flights, and consisting of approximately 3.7 million records. This combined flight track dataset is used by the gridding code to calculate species emissions in the 3-dimensional SCOS97 domain.

The last part of the pre-processing involved downloading the US EPA latest EDMS (version 3.2.2.3) aircraft-engine-APU relationship, engine emission factors, and APU emission factors data files (Ref. 6). This dataset contains emission factors for taxi/idle, takeoff, climbout, and descent operating modes. A cruise mode was added, and defined as the average of the climbout and descent emission rates. The species are CO, HC, NOX, SOX and PM. Engine (and hence aircraft) fuel flow rate was also obtained from the EDMS dataset.

Good correlation was found, over the 650 EDMS aircraft types, between aircraft fuel flow rate and aircraft emission factors: namely an emission factor is a fixed fraction of the fuel flow rate. This correlation was used to 'fill in' missing emission factors in the EDMS engines data. A similar procedure was used to 'fill in' missing APU emission factors. However, there is no APU PM emission factor data in the EDMS dataset.

The aircraft types in the EDMS emission factor files are 20-character codes, which do not correspond to the 3- or 4-character aircraft type codes in the above FAA flight track dataset. There are approximately 650 aircraft types in the EDMS emission factors dataset, and approximately 620 aircraft types in the FAA flight track dataset. However, of these 620, only 240 account for 90% of the flight track data points. These 240 were hand-compared with the EDMS 650 aircraft types, to assign an EDMS aircraft type to each of the 240 FAA flight track aircraft types. These 240 aircraft types were then assigned engine emission factors from the EDMS data, multiplied by the number of engines on each aircraft type (also EDMS data). APU emission factors were similarly assigned, where available. Where APU data was not available for a specific aircraft type, average values over all the APUs were used.

For the remaining 380 FAA aircraft types, comprising 10% of the flight track data points, and for the 'blank' FAA aircraft types which were estimated to be commercial jets (250 knot or higher speed filter, 15% of the 'blanks'), a default 'B73S' (Boeing 737S) aircraft type was assigned. The difference in emissions between a 'B73S' aircraft type for these defaults, and ignoring the over 250 knot defaults, is 10%.

V. Gridding Code Description.

A 3-dimensional grid was developed for the SCOS97 domain. Aircraft flight tracks were obtained from FAA (Federal Aviation Agency) radar transponder returns datasets, for the SCOS97 episode dates (Section IV). Numerical integration of engine emission factors was performed, along the flight tracks of the commercial jets in the dataset through the 3-dimensional grid. Engine emission factors varied with the aircraft operating mode: takeoff, climbout, cruise, descent, taxi/idle with APU, APU only. Generated CO, HC, NOX, SOX and PM emissions were placed in the grid cells along the flight track for the hours throughout the day.

The gridding code was written to 'fly' the aircraft through the 3-D SCOS97 domain, select operating mode from the flight track, and dump corresponding emissions in the grid. Grid cell loadings are output in MEDS format, and can be summarized by altitude range. Calendar time interval is an input.

Note that in this ARB approach, the number of aircraft in a given hour, aircraft types, emissions at or near various airports, time in the various operating modes, altitude ranges, and latitude-longitude ranges, are generated by the gridding code from the flight tracks. Hence these values can be, and typically are, different from the SCAQMD values.

A typical run involving all of the SCOS97 episodes, i.e. 360,000 flight tracks, uses approximately 34 hours of Silicon Graphics O_2 (195-MHz) CPU time. This is because the lower altitude layers are only a few feet thick, requiring time steps of the order of thousandths of a minute.

VI. Gridding Code Structure.

The gridding code structure is shown in Figure 1. It is written in FORTRAN-77. All subroutines are internally documented with variables and nomenclature lists, and extensive comments.

‘Mesh.f’ is the main program. Its input files are in directory ‘input_dat’. It writes all output to files in directory ‘output_dat’. ‘Mesh.f’ reads the dates for which emissions calculations are to be performed from input file ‘control.mesh’. An EOF (end of file) on ‘control.mesh’ terminates the execution.

After reading a date from ‘control.mesh’, ‘Mesh.f’ loops over the hours of the day. It calls the subroutine ‘Meshit.f’, which performs the emissions calculations for each day, hour and operating mode, by numerically integrating engine emissions along all flight tracks which fall within the mesh of the SCOS97 3-D domain, within the specified date and hour. It does this for the five species: CO, HC, NOX, SOX and PM. The emissions are placed within the appropriate cells of the 3-dimensional domain.

An output file is generated, in MEDS format, for each day of the calculation. Each record (line) in this file gives cell x- and y- grid cell numbers (either 2- or 5-Km. spacing), aircraft operating mode, date, hour, source elevation, and emissions (kg/hour) for the 5 species.

‘Meshit.f’ calls ‘Grabtraj.f’ (grab trajectory), to extract a flight track from the combined FAA dataset. The dataset is organized in sequential order of the start time of each of the flight tracks. An associated pointer file points to the first record in each of the flight tracks. Initially, ‘Grabtraj.f’ finds the first flight track which has a final time greater than or equal to the start of the hour time (the first flight track), and the last flight track which has a start time less than or equal to the end of hour time (the last flight track). These searches are performed by binary splitting searches of the pointers in the pointer file.

The flight tracks dataset contains 3.7 million records (lines), each of which specifies FAA flight number, airline aircraft ID, FAA aircraft type (4-character code), time (GMT minutes from midnight AM, 1 Jan. 97), aircraft speed (knots), altitude (ft/100 above mean sea level (msl)), longitude and latitude (in degrees), aircraft operating mode (takeoff, climbout, cruise, descent, taxi/idle, APU only). The records have been sorted by FAA flight number and by time within each flight track.

‘Grabtraj.f’ then sequentially ‘feeds’ a flight track, starting with the first and ending with the last, for each call from ‘Meshit.f’. After the last flight track, ‘Grabtraj.f’ returns a negative value for the number of points in the flight track, indicating to ‘Meshit.f’ that there are no more flight tracks within the specified time interval.

‘Grabtraj.f defines aircraft operating modes along the flight track: 1) Takeoff , 2) Climbout, 3) Cruise, 4) Descent, 5) Taxi/Idle with APU (auxiliary power unit), 6) APU only. It makes sure that taxi/idle, APU, and takeoff time intervals along the flight track match EPA standards, allowing for varying inversion layer thicknesses and taxi times at the various airports. It calls ‘Planemsf.f’ for the aircraft (engine) and APU emission factors, for the various aircraft operating modes. It calls ‘Airports.f’, to verify and define airport locations at the beginning or end of a flight track.

VII. Post Processing of ‘Grid’ Code Results.

Post processing involves:

a) ‘layers.f’ summarizes results by altitude layers.

b) ‘LTO.f’ summarizes landings and takeoffs.

c) ‘average.f’ summarizes low and high altitude layers results from ‘layers.f’.

d) ‘timeit.f’ summarizes times in the various aircraft operating modes.

e) ‘excelgen.f’ generates Excel files for graph generation.

f) ‘dxgen.c’ is a sequence of 24 custom-written Fortran and C subroutines for 3-dimensional graphics of cell emissions, using IBM Data explorer.

VIII. Conclusion.

Please refer questions and comments to:

Arthur M. Collins
Control Strategy Modeling Section
Planning and Technical Support Division
California Air Resources Board
1001 I St.
Sacramento, CA 95814
acollins@arb.ca.gov

IX. References.

1) "South Coast Aircraft Emission Inventory: Baseline for 1997", DRAFT (December 1, 1997). Prepared for: South Coast Air Quality Management District, Diamond Bar, California. Prepared by: Energy and Environmental Analysis, Inc., 1655 North Fort Meyer Drive, Arlington, VA 22209.

2) "Aircraft Takeoff and Landing Statistics", Bureau of Transportation Statistics (BTS), U. S. Dept. of Transportation (Undated).

3) "World Jet Inventory", Jet Information Services, Inc. (Undated).

4) "Emissions and Dispersion Modeling System (EDMS) Reference Manual", Section 3.1.1, Emissions Calculations, Aircraft Activity, Time-In-Modes (TIM)

5) "FAA Flight Track Data Files, Selected 1997 Episodes", John Cheng, Dimensions International Inc., 4501 Ford Avenue, Suite 1200, Alexandria, VA 22302, jcheng@dimen-intl.com, 703.998.0098 x129.

6a) "EDMS (Emissions and Dispersion Modeling System) Version 3.2.2: CO, NOx, SOx and HC Aircraft/Engine Emission Factors Files: 'Aircraft.dbf', Aircraft Name, Number of Engines, Operating Mode, Time in Mode. 'Eng-Def.dbf': Aircraft Name, Engine Name. 'Eng-Ef.dbf': Engine Name, Operating Mode, Kg/Hr: CO, HC, NOx, SOx, Fuel Flow Rate", 3 Jan. 2001.

6b) "PM Versus Fuel Flow Rate Engine Emission Factor Correlations; File 'emsfacpm-scos.xls'. Compiled from AP-42'85 and CA-FIP'94", John R. Pehrson; Camp, Dresser and McKee, Inc.; 18881 Von Karman Ave., Suite 650; Irvine, CA 92612; 8 Jun 1999.

Figure 1 – Gridded Program Flow Chart